ANGULAR CORRELATION α-PARTICLES IN THE REACTION $^{12}C(\gamma, 3\alpha)$ AT THE FORMATION OF ^{8}Be NUCLEUS IN THE FIRST EXCITED STATE

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(Received April 11, 2011)

Investigation of channel formation of the first excited state of ^{8}Be nucleus in $^{12}C(\gamma, 3\alpha)$ reactions is executed. The methodic of kinematical models of $\gamma +^{12} C \to \alpha_1 +^{8} Be^{*}$ reaction is developed and is correctly selected α_1-particle. The angular distributions of $\gamma +^{12} C \to \alpha_1 +^{8} Be^{*}$ reaction and channel of disintegration of nucleus $^{8}Be^{*} \to \alpha_2 + \alpha_3$ are measured. The elements of density matrix of $^{8}Be^{*}$ nucleus and spherical spin-tensors characterizing polarization of $^{8}Be^{*}$ nucleus definite.

PACS: 25.20.-x

1. INTRODUCTION

At present studies of the systems with the selected orientation of spin is given in nucleus physicist big attention [1]. Along with extremely difficult experiments with use of the polarized beams and targets the method of reception of the information on properties of the oriented systems, based on studying of functions of correlation of formation of the excited states and their disintegration in three-particles reactions of type $A(\gamma, a)B^{*}(b, c)$ is developed. Amplitude of such reaction of the consequent type is factorized on amplitude of reaction $A(\gamma, a)B^{*}$ and amplitude of decay $B^{*} \to b + c$ [2]. The characteristic of the particle B^{*}, having nonzero spin and being in the excited states, are rather sensitive to change of the mechanism of reaction. The analysis of such parameters enables to get additional information about nucleus structure, nuclear interaction and nucleon associations.

Earlier [3] was us it is shown, that disintegration of nucleus of carbon on α-particles goes as consequent process with formation of nucleus on intermediate stage: $\gamma +^{12} C \to \alpha_1 +^{8} Be^{*}$ (I) and $^{8}Be^{*} \to \alpha_2 + \alpha_3$ (II). In this report the analysis of events in area of the first maximum of total cross sections $^{12}C(\gamma, 3\alpha)$ reactions will be executed - at photon energies of up to 22 MeV. Here possible channel of the formation of ^{8}Be nucleus in the ground state and first excited states. The partial channel of the formation the ground state of ^{8}Be nucleus is reliably selected [4], therefore is not a background for remaining events.

The use in the experiment 4π-detector (a diffusion chamber [5] placed in a magnetic field) enables to measure the angular distributions in the systems (I) and (II), and define amplitudes of the formation and disintegration of ^{8}Be nucleus. The matrix elements of amplitudes can be expressed through the elements normalized of the density matrix ρ_{ik} [6, 7] and depends only from polarization $t^{00,IM}$ even rank. Determination of the density matrix gives unique possibility to define the polarization tensor of ^{8}Be nucleus [2], which includes information not only about the spin state of this nucleus, but also about all nuclear reaction on the whole. Angular distributions in in the system (I) the first element of spin-tensor of the density matrix ρ_{00} is presented only. Different from ρ_{00} elements spin-tensor of the density matrix of ^{8}Be nucleus (determined by the angular distributions of the system (II)) are not simply additional parameters, but descriptions determining the mechanism of reaction $^{12}C(\gamma, 3\alpha)$.

2. DETERMINATION α_1-PARTICLES, ACCOMPANYING FORMATION OF ^{8}Be NUCLEUS

The energy of the relative motion (E$_x$) of two α-particles is [6]

$$E_x = \frac{(\overrightarrow{p}_i - \overrightarrow{p}_k)^2}{4m}, \qquad (1)$$

where i, k are their numbers and p and m are their 3-momentum and mass, respectively. Because of particle identity, we were unable to select a pair produced upon ^{8}Be in constructing E_x distributions, we therefore used three values of E_x to represent each event. In Fig.1,a, the distributions are shown by light points. The histogram step by 0.25 MeV, and the points were placed in the middle of intervals. The displayed errors are purely statistical.

Distribution is compared to the phase [6]:

$$f(E_x) = \sqrt{E_x} \cdot \sqrt{E_x^{max} - E_x}, \qquad (2)$$

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where E_x^{max} - maximum kinetic energy in the system of two α-particles, equal to total energy all particles in s.c.m. For a continuous photon spectrum, phase distributions were calculated step by step. First, this was done for photon-energy intervals 1 MeV wide. The area under the curve was normalized to the number of events per interval. After that, summation of probabilities was performed for identical intervals of energies E_x. In Fig.1,a phase distributing it is shown a solid curve.

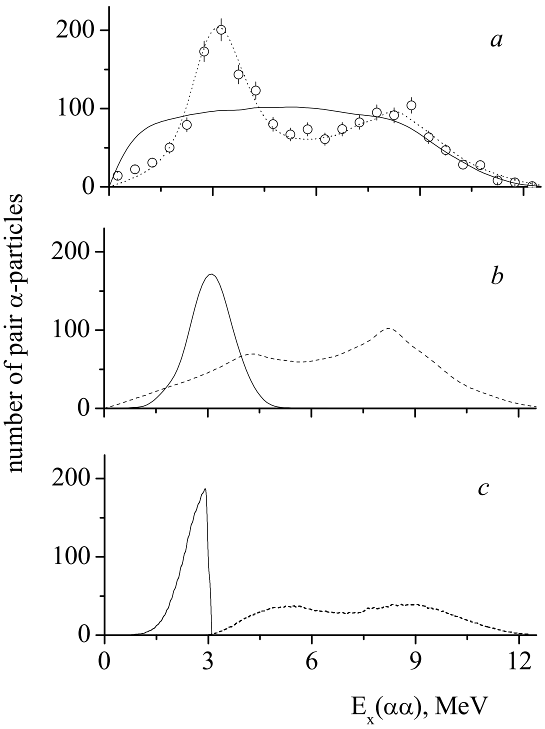

Fig.1. *Excitation energy distribution for the system of two α-particles*

The experimental distributions of pairs α-particles differs from a phase and has two maxima, that whose parameters are $E_0^1 = 3.12 \pm 0.04$ MeV and $\Gamma^1 = 1.89 \pm 0.07$ MeV and that whose parameters are $E_0^2 = 8.13 \pm 0.12$ MeV and $\Gamma^2 = 4.17 \pm 0.24$ MeV. The parameters of the first maximum are near to similar means of the first excited state of ^8Be nucleus ($E_0 = 3.04$ MeV and $\Gamma = 1.5$ MeV from the known compiling of spectroscopic data [8]).

For the analysis of distributions in Fig.1,a the method of mathematical model $^{12}C(\gamma, 3\alpha)$ reactions was developed. On the basis of this model, one can deduce the distribution of energies of the relative motion of two α-particles, employing parameters of known levels of the ^8Be nucleus, a specific form of angular distributions in the rest frame of two α-particles, and the experimental energy dependence of the total cross section. The form of angular distributions in the reference frame commotion with the center of mass $\alpha_1 +^8 Be^*$ system has no effect on the E_x distribution since it characterizes the rotation of the system as a discrete unit. The angular distribution of α-particles in the rest frame of the ^8Be nucleus play a significant role in the E_x distribution. We chose the form of the angular distribution as follows: the experimental angular distribution in the system of rest of the E_x nucleus were obtain, energy of excitation the ^8Be nucleus is near to the first level [8] and executed approximation by trigonometric functions. A polar angle was counted off from direction of motion of the ^8Be nucleus and took into account the measurement errors in the particle momenta is 4 MeV/c and in the polar angle is 2° [3]. As in a model there is possibility simply to identify α-particles, two types of distributing on energy of excitation of pair α-particles were obtain - resonance function of excitation of the ^8Be nucleus ($\alpha_2\alpha_3$) (in the Fig.1,b solid curve) and background distributing (on the Fig.1,b dashed curve), where one of particles α_1($\alpha_1\alpha_2$ and $\alpha_1\alpha_3$).

The result obtained on the basis of this model (sum of the resonance and background distributing) for the channel of formation of the ^8Be nucleus in the first excited state is shown in the Fig.1,a dashed curve. The agreement of model with the experiment allows to equate the first resonance with the first excited state of the ^8Be nucleus, and second to consider a background. From Fig.1,b follows that resonance and background distribution has a zone of the overlapping that in the experiment complicates the selection α-particles, giving contribution to resonance. With the purpose of search of terms for the reliable division of distributing was executed the following:

a) intervals on energy γ-quantum E_γ were varied, that causes change of background part;

b) restraints on energy of excitation of resonance pair α-particles E_x were imposed (diminishes a zone of the overlapping).

It is definite, that at $E_\gamma = 16...20$ MeV and $E_x(\alpha_2\alpha_3) \leq 3.04$ MeV the resonance and background pairs α-particles were reliably divided and, consequently, was exactly determined α_1. In the Fig.1,c the results of model at optimum conditions are presented.

To make sure, that by such limitations the structure of the angular distributing was not changed in the systems of rest (I) and (II), verification of influencing of choice of conditions of separation of resonance and background parts on the proper angular distributing was executed. By means of modeling the angular distributing in different systems of rest in two variants were built: with limitation for E_γ and E_x and without. It is definite, that limitations on E_γ and E_x do not change type of the angular distributing.

3. ANGULAR DISTRIBUTIONS

Reliable selection in the experiment α_1-particles at formation of first excited the states of ^8Be nucleus allows correctly to build the angular distributing in the systems (I) and (II).

For the unpolarized beam the differential section of the investigated reaction of successive type can be written down as product of cross section of formation of ^8Be nucleus in the system of center of reaction (I) and correlation function of the disintegration of ^8Be nucleus (II) $W(\alpha,\beta)$ [2]:

$$\frac{d^2\sigma}{d\theta d\Omega_{\alpha,\beta}} \sim \frac{d\sigma}{d\theta}\cdot W(\alpha,\beta)\,, \qquad (3)$$

where θ - the angle of output of ^8Be nucleus in the system (I) (axis of quantum - along direction motion of photons); α - polar, β - azimuthal angles in the system (II) (axis of quantum - along direction of motion ^8Be nucleus).

3.1. REACTION OF FORMATION OF ^8Be NUCLEUS

Differential sections of $d\sigma/d\theta$ it was determined in the system of rest $(\alpha_1 +^8 Be)$ (I). Results are presented by light points in the Fig.2,a. Distributions are symmetric in relation 90°.

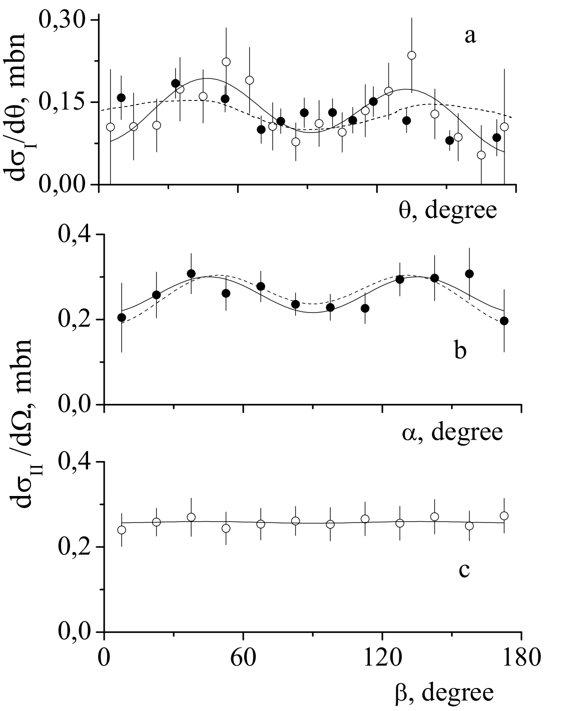

Fig.2. *Angular distributions: a) - $\gamma +^{12} C \to \alpha_1 +^8 Be^*$, ○ - our experiment, ● - [10], solid curve - fitting of Legendre polynomials, dashed curve - [11]; b), c)– system of $^8Be^* \to \alpha_2 + \alpha_3$ (● - polar angle α, ○ - azimuthal angle β, our experiment), solid curves and dashed curve - fitting corresponding angles*

To the solid curve on the fig.2a fitting of our experimental data on MNK is shown by factorization [9]:

$$\frac{d\sigma}{d\theta} = \sum_{i=0}^{4} c_i P_i(\theta)\,, \qquad (4)$$

where $P_i(\theta)$ - the Legendre polynomials, c_i - coefficients at polynomials.

Results of fitting: c_0=14.05±0.91, c_1=1.33±1.35, c_2=1.59±1.77, c_3=-0.37±1.85, c_4=-9.42±2.11, $\chi^2/DoF = 0.64$. In the parameters of c_1, c_2 and c_3 means and error of their measuring are near.

In work [9] multipole amplitudes of the reaction photodisintegration $J^\pi + 0^+ \to J^\pi(^{12}C) \to 2^+ + 0^+$ with formation of the compound of ^{12}C nucleus are definite. The finish state corresponds to the explored in our work channel ($^8Be + \alpha_1$). Calculations are executed for the spins of ^{12}C nucleus $J^\pi = 1^-, 1^+$ and 2^+. The coefficient of c_4 arises up only at clean E2-transition with the high values of the orbital moment L. Quantitative correlations of coefficients in our experiments can correspond to multipoles with LJS=222 and LJS=422, where J - total moment, S - spin of the finish system. At the same time, in the known tables of spectroscopy data [11], there are no levels of ^{12}C nucleus with $J^\pi(^{12}C) = 2^+$ and isotopspin T=0, able to realize this process.

By dark points in the Fig.2,a experimental results [10] are presented. The analysis of the angular distributing in this work showed that the mixture E1- and E2-transitions with a considerable role from E2-transitions is prevailing. The not strict selection of channel of reaction is possible explanation of such divergence with our data. By a pair α-particles, formative of ^8Be nucleus, those at which energy of excitation is found near-by were considered (2.95±0.09) MeV. And α-particles, accompanying to formation of ^8Be nucleus, was considered the first out off. However, as visible (the Fig.1,b), it not for certain divides the resonance and background distributing.

In theoretical work [12] contribution of coulomb and nuclear interactions of products reactions on the angular distributing of primary α-particles the $^{12}C(\gamma,3\alpha)$ reaction with transition on the level of 2^+ of ^8Be nucleus within the framework of model of nucleon associations is explored and their substantial role is shown. Consideration of the final state interaction (the dotted curve on the Fig.2,a) gives a considerable isotropic constituent into calculation on comparison with clean E1- and E2-transitions. Quality a curve explains the results of experiment. A conclusion is done, that the reaction can proceed without formation of the compound ^{12}C nucleus. However calculation of angular distributions in the system of rest of ^8Be nucleus is absent.

3.2. DISINTEGRATION OF ^8Be NUCLEUS

To get the angular distributing of products of disintegration in the system of his rest of ^8Be nucleus (II), it must integrated expression (3) on $d\theta$ and $d\Omega_{\alpha,\beta}$. The correlation function $W(\alpha,\beta)$ it is possible to express through he elements normalized of the density matrix ρ_{ik} [6, 7]. For the 2^+ state of ^8Be nucleus and taking to account that spin α-particles equal to zero here only one amplitude which relies only on polarization of $t^{00,IM}$ even ranks. Here zeros mean the unpolarized initial state, I - complete moment of the system and M - projection of complete moment. In our experiment from insufficient statistical material well-being it is necessary to execute integration on the angles of output of particle α_1. It lays on limitation: M=0. Dependence of angular distributions in the system of rest of ^8Be nucleus is [6]:

$$W \propto \sum_{MM'} e^{i(M-M')\beta} d_{M0}(\alpha) d_{M'0}(\alpha)\rho_{MM'}\,, \quad (5)$$

where M, M$'$ are projections of complete moment of ^8Be nucleus. Matrix elements of the operator of turn (d-functions) for the correspondent moments is taken from tables [2, 6]. For expansion was used hermicity of the density matrix $\rho_{MM'}$. Combining elements at the identical values of exponent:

$$W \propto p_0 + p_1 cos\beta + p_2 cos2\beta + p_3 cos3\beta + p_4 cos4\beta\,, \quad (6)$$

where

$$\begin{aligned}
p_0 &= \frac{(3cos^2\alpha-1)^2}{2}\rho_{00} + 3sin^2\alpha cos^2\alpha\rho_{11} + \frac{3}{4}sin^4\alpha\rho_{22}\,,\\
p_1 &= \frac{3}{2}(sin^3\alpha cos\alpha Re\rho_{21} - sin^2\alpha cos^2\alpha Re\rho_{10})\,,\\
p_2 &= \frac{\sqrt{6}}{4}sin^2\alpha(3cos^2\alpha-1)Re\rho_{20} - \frac{3}{2}sin^2\alpha cos^2\alpha Re\rho_{1-1}\,,\\
p_3 &= -\frac{3}{2}sin^2\alpha cos^2\alpha Re\rho_{2-1}\,,\\
p_4 &= \frac{3}{8}sin^4\alpha Re\rho_{2-2}\,.
\end{aligned} \quad (7)$$

From insufficient poor statistic of experiment, expression (6) on azimuth (β) and polar (α) degrees is integrated and dependencies are define accordingly on α and β.

A) DISTRIBUTION ON A POLAR ANGLE

Distributing on a degree α is resulted in a Fig.2,b closed circles. For the 2^+ state of ^8Be nucleus differential sections after integration on an azimuth degree (β) fitting (in the Fig.2,b solid curve) is executed by the expression $F(\alpha) = a_0(3cos^2\alpha-1)^2 + a_1 sin^2\alpha cos^2\alpha + a_2 sin^4$. Parameters of the fitting a_0=0.215±0.017, a_1=1.629±0.066, a_2=0.642±0.067, χ^2/DoF=1.65 are used for determination of elements of the density matrix ρ: $a_0 = 0.5\pi\rho_{00}$, $a_1 = 0.5\pi\rho_{11}$ and $a_2 = 1.5\pi\rho_{22}$.

Their rate normalized is executed with the use of expression $sp(\rho) = 2\rho_{22} + 2\rho_{11} + \rho_{00}$=1. As result of ρ_{00}=0.124±0.001, ρ_{11}=0.079±0.003, ρ_{22}=0.124±0.013. Density matrix of ^8Be nucleus factorized on spherical spin-tensor t^{IM}, characterizing polarization of ^8Be nucleus: t^{00}=1 - normalization requirement, $t^{20} = Sp(\tau_{20}\rho)$=2.39$\rho_{22}-1.2\rho_{11}-1.2\rho_{00}$, $t^{40} = Sp(\tau_{40}\rho)$=0.53$\rho_{22}-2.14\rho_{11}$+1.6$\rho_{00}$. Using the means of elements of the density matrix, we will define statistical tensors: t^{20}=0.053±0.021 and t^{40}=0.096±0.018. The angular distributing can be factorized [2] on the Legendre polynomials, statistical tensors will be coefficients at which

$$W = A(1 + t^{20}P_2(cos\alpha) + t^{40}P_4(cos\alpha)) \quad (8)$$

The results of fitting expression (8) on a Fig.2,b dashed curve are shown. Parameters of fitting: A=0.268±0.009, χ^2/DoF=0.82.

B) DISTRIBUTION ON AN AZIMUTH ANGLE

Distributing on a degree β is resulted in a Fig.2,c open circles. For the 2^+ state of ^8Be nucleus differential sections after integration on an polar degree (α) fitting (in the Fig.2,c solid curve) is executed by the expression $F(\beta) = b_0 + b_1 cos2\beta + b_2 cos4\beta$. Parameters of the fitting b_0=60.711±0.799, b_1=0.071±1.131, b_2=-0.416±1.131 and χ^2/DoF=1.77 are used for determination of elements of the density matrix ρ: $b_0 = 9\rho_{22} + 12\rho_{11} + 11\rho_{00}, b_1 = 2.45Re\rho_{20} - 12\rho_{1-1}$ and $b_2 = 9\rho_{2-2}$. The parameters of b_1 and b_2 within the limits of errors are near to the zero.

The complete section of disintegration of ^8Be nucleus after integrated on α and β expression (6): $\sigma_{\alpha,\beta} \sim 2\pi(\frac{\pi}{32})(9\rho_{22} + 12\rho_{11} + 11\rho_{00})$. The means of the density matrix were definite before on distributions of polar degree α and $\sigma_{\alpha,\beta}$=2.111±0.163. It is found in the consent with data [3], where partial cross section of formation the first levels of ^8Be nucleus σ_1=2.29±0.09.

4. CONCLUSIONS

In the $\gamma + ^{12}C \to \alpha_1 + ^8Be^*$ reaction the channel of formation of ^8Be nucleus in the first excited state is investigated. The methodic of kinematical models reactions is developed. It is definite the condition for correct selection α_1-particle, accompanying formation of ^8Be nucleus.

The angular distributions of $\gamma + ^{12}C \to \alpha_1 + ^8Be^*$ reaction and channel of disintegration of nucleus $^8Be^* \to \alpha_2 + \alpha_3$ are measured.

In the system $\alpha_1 + ^8Be^*$ the fitting by the Legendre polynomials is executed and coefficients at polynomials are definite: c_0=14.05±0.91, c_1=1.33±1.35, c_2=1.59±1.77, c_3=-0.37±1.85, c_4=-9.42±2.11, χ^2/DoF=0.64. Within the framework of model of formation of compound $^{12}C^*$ nucleus experimental data can be accounted for in clean E2-transition with the high values of the orbital moment L. However in the investigated region of energies there are no levels of carbon with the proper quantum characteristics.

In the system $\alpha_2+\alpha_3$ the dependence on polar (α) and azimuth (β) angles is explored. The correlation function $W(\alpha,\beta)$ it is possible to express through he elements normalized of the density matrix ρ_{ik}. The angular distributions fitting by the functions $F(\alpha) = a_0(3cos^2\alpha - 1)^2 + a_1 sin^2\alpha cos^2\alpha + a_2 sin^4$ and $F(\beta) = b_0 + b_1 cos2\beta + b_2 cos4\beta$ was executed. The coefficients a_0, a_1, a_2 (a_0=0.215±0.017, a_1= 1.629±0.066, a_2=0.642±0.067) and b_0, b_1, b_2 (b_0=60.711±0.799, b_1=0.071±1.131, b_2=-0.416±1.131) are definite.

The elements of density matrix (ρ_{00}=0.124±0.001, ρ_{11}=0.079±0.003, ρ_{22}=0.124±0.013) and spherical spin-tensors (t^{20}=0.053±0.021 and t^{40}=0.096±0.018), characterizing polarization of ^8Be nucleus was calculated.

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УГЛОВАЯ КОРРЕЛЯЦИЯ α-ЧАСТИЦ В РЕАКЦИИ $^{12}C(\gamma,3\alpha)$ ДЛЯ КАНАЛА ОБРАЗОВАНИЯ ЯДРА ^8Be В ПЕРВОМ ВОЗБУЖДЕННОМ СОСТОЯНИИ

С.Н. Афанасьев

Выполнено исследование канала образования первого возбужденного состояния ядра ^8Be в реакции $^{12}C(\gamma,3\alpha)$. Разработана методика кинематического моделирования реакции $\gamma +^{12} C \to \alpha_1 +^8 Be^*$ и корректно выделена α_1-частица. Измерены угловые распределения реакции $\gamma +^{12} C \to \alpha_1 +^8 Be^*$ и канала распада ядра $^8Be^* \to \alpha_2 + \alpha_3$. Впервые определены элементы матрицы плотности ядра $^8Be^*$ и сферические спин-тензоры, характеризующие поляризацию ядра $^8Be^*$.

КУТОВА КОРЕЛЯЦIЯ α-ЧАСТИНОК У РЕАКЦIЇ $^{12}C(\gamma,3\alpha)$ ДЛЯ КАНАЛУ УТВОРЕННЯ ЯДРА ^8Be В ПЕРШОМУ ЗБУДЖЕНОМУ СТАНI

С.М. Афанасьєв

Виконано дослiдження каналу утворення першого збудженого стану ядра ^8Be в реакцiї $^{12}C(\gamma,3\alpha)$. Розроблено методику кiнематичного моделювання реакцiї $\gamma +^{12} C \to \alpha_1 +^8 Be^*$ i коректно видiлена α_1-частинка. Вимiряно кутовi розподiли реакцiї $\gamma +^{12} C \to \alpha_1 +^8 Be^*$ i каналу розпаду ядра $^8Be^* \to \alpha_2 + \alpha_3$. Вперше визначено елементи матрицi густини ядра $^8Be^*$ i сферичнi спiн-тензори, що характеризують поляризацiю ядра $^8Be^*$.